SODIUM FIRES AT FAST REACTORS: RF STATUS REPORT

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Abstract

Scientific and engineering studies carried out in Russian Federation since 1992 up to 1996 in the sodium fire area and their main results are described. A review of activities on modification of the computer codes BOX and AERO developed at IPPE for calculating sodium fire consequences is given. Results of analysis of possible accidental situations at currently designed BN-800 reactor NPP with the use of these codes are presented. Sodium leaks occurring at our domestic fast reactors are briefly analyzed. Experimental work performed are described. Results of comparative analysis of common-cause and sodium fire hazards for fast reactor NPP are presented.

1. COMPUTER CODES

1.1. The computer codes BOX and AERO

For calculation of sodium fire accident consequences at fast reactor nuclear power plants the computer codes BOX and AERO have been developed at IPPE. The code BOX calculates the sodium pool fire accidents. By this code the following most important parameters are determined:

- temperature and pressure of gaseous medium in the room;
- temperature of structures;
- mass concentration of sodium fire aerosol products in the room;
- air (or gas) ingress or leakage flow rates through points of untightness;
- air (or gas) flow rates of intake and exhaust ventilations (if a fire takes place in a ventilated room);
- aerosol mass release rate and total mass release from the fire room (into the atmosphere and/or into the neighbouring rooms).

Main input data of the code are:

- temperature and mass of spilled sodium, leakage flow rate (time of leakage);
- geometrical dimensions of the room (length, width, height, wall thickness);
- initial temperatures of gaseous medium in the rooms and of structures;
- the value of gaseous-medium initial pressure in the rooms;
- characteristics of room lining and of thermal insulation between lining and concrete (if lining and/or insulation are present);
- parameters of room leak-tightness;
- initial values of intake and exhaust ventilation flow rates.

The code AERO has been developed for calculation of potentially possible irradiation doses to population during the design and beyond design basis accidents with radioactive sodium burning at the BN-type NPP. In the course of such accidents the sodium aerosols can be released to the atmosphere. This code calculates individual irradiation doses from the aerosol cloud both due to external irradiation and due to inhalation (a total-body dose and single organs doses), as well as from fallout radioactivity species. The code allows also to calculate the toxic effects of sodium aerosols to population (including those due to non-radioactive releases).

Main input parameters of the code are:

- mass release rate or integral mass release (which are calculated using the code BOX);
- release conditions (a height of the release source, velocity and temperature of ventilation air released);
- radionuclide composition of a release;
- conditions for aerosol transport in the atmosphere.

In more detail the codes BOX and AERO are described in [1, 2].

1.2. Modification of the codes

Adequacy of calculation results obtained by these codes is being attached much importance, because they are used for the analysis of probable accidental situations at fast reactor NPPs in operation and currently designed. Work on improvement of the codes and their verification is continuously under way.

1.2.1. The BOX code

The BOX code was initially developed for calculation of processes within a single room and for a case of large fires. Recently, work on it was carried on in two principal directions:

- modification aimed at providing a possibility of calculation within rooms adjacent to the accidental one;
- checking a possibility of using the code for calculation of processes at small-scale fires.

First of all, it was necessary to introduce algorithms allowing to calculate aerosol transport between reactor building rooms and the mass concentration in each room. For calculation of mass concentration in an adjacent room, C_n, the following equation was used:

$$\frac{dC_n}{dt} = I_n - \left(1.7*10^{-3}\frac{S_{fl,n}}{V_n} + 3*10^{-5}\frac{S_{w,n}}{V_n}\right)C^{0.4}*C_n - \lambda_{out}C_n \qquad (1)$$

where

C is aerosol concentration in the accidental room (g/m^3),
$S_{fl,n}$ is floor area of the adjacent room (m^2)
$S_{w,n}$ is total area of adjacent room walls (m^2),
V_n is adjacent room volume (m^2),
λ_{out} is a parameter of aerosol removal from the adjacent room by means of ventilation (s^{-1}),
t is time (s).

The equation is valid for values of $C>0.5$ g/m^3, and for $C<0.5$ g/m^3 in this equation 7.4×10^{-4} should be written instead of 1.7×10^{-3} . The index n indicates that parameters of room into which aerosols enter are taken. The value I_n represents the rate of aerosol ingress into this room. Its value is

$$I_n = \frac{C * L_n}{V_n} , \qquad (2)$$

where the value of L_n- the flow rate of ingress of gaseous medium with aerosols into this room - is determined in the course of calculation by the BOX code.

Verification of the code for small-scale fires was carried out in the process of experiments on investigation of sodium aerosol generation and transport [3]. The thermal effects at small fires within technological rooms playing no significant part, primary attention was being given to calculations of aerosol mass concentration. The results of verification are satisfactory. In Fig. 1, experimental and calculation curves for one of the tests are presented.

1.2.2. The AERO code

Modification of the AERO code was made mainly with the aim of taking into account the effect of humidity upon the particle dispersion characteristics at their propagation in the atmosphere. It is known that at sodium fire aerosol products transport in the atmosphere the chemical interaction of sodium oxides with its components - steam and carbon dioxide gas - takes place. If relative humidity of air exceeds 35% a change of aerosol particles physical structure occurs. They transform from dry particles into liquid drops. The particle matter initially representing sodium oxides Na_2O and Na_2O_2 transforms initially into hydroxide NaOH and then into carbonate $Na_2CO_3 \times nH_2O$ whose hydration degree depends on atmosphere humidity. Therewith the density as well as the dispersion characteristics of aerosols are changing. It results in variation of particles sedimentation parameters that should be taken into account at calculating the doses to population at accidents.

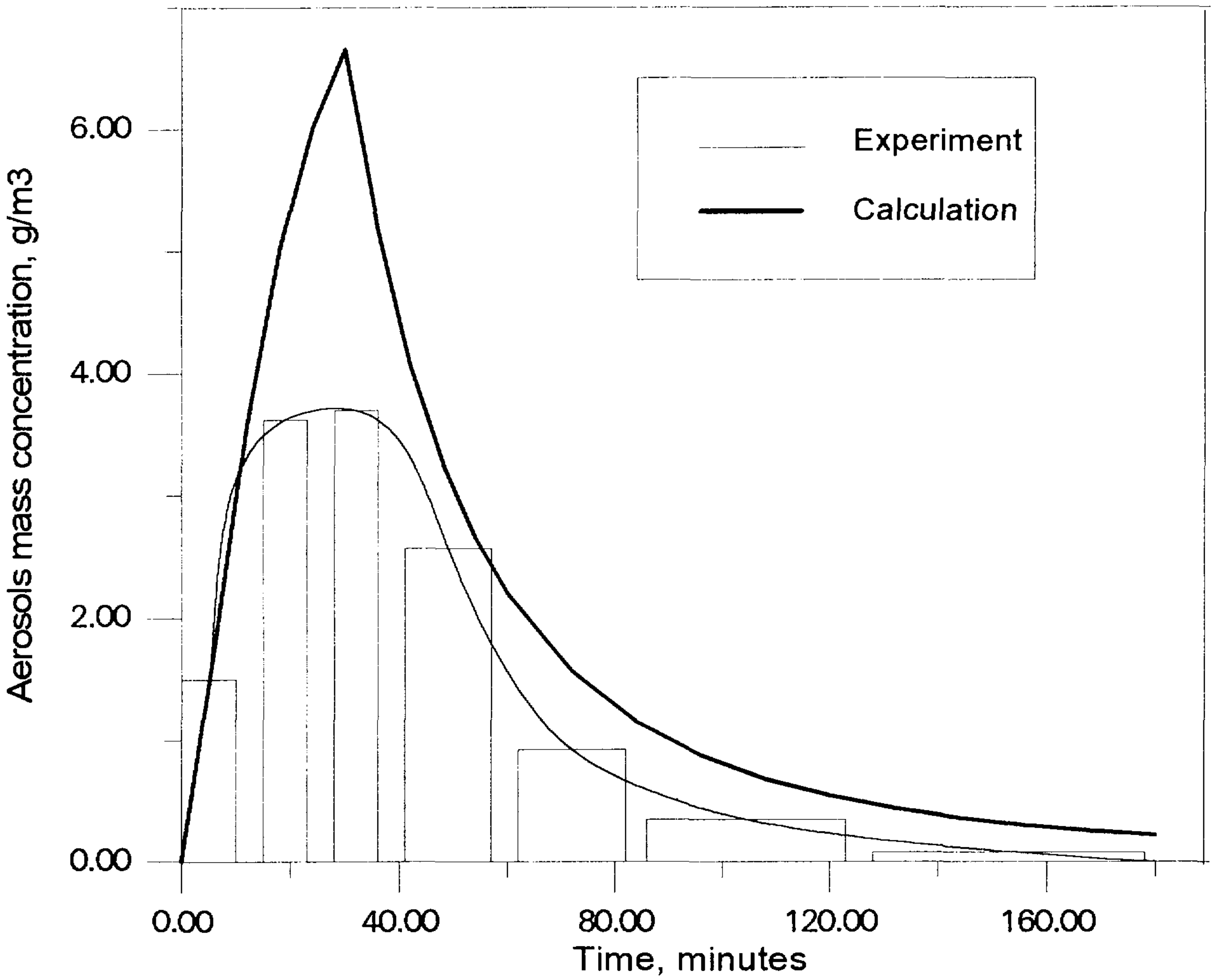

Fig. 1. Experimental and calculated aerosols mass concentration.

For taking into account these processes in the AERO code a series of experimental and theoretical studies were carried out at IPPE. As a result the dependence of n on relative atmosphere humidity H has been obtained presented in Fig. 2. The curve part for $35\% < H < 92\%$ was plotted on the basis of laboratory studies carried out at IPPE, that for $H \geq 92\%$ was calculated theoretically.

Formulas has been developed that allow to calculate the radius of formed hydroxide particles and then of carbonate particles for a given relative humidity of air on the basis of some initial oxide particle radius. Using these relationships and data on particle densities [4] the variation of particles gravitational sedimentation rate in the atmosphere can be determined by the formula

$$\frac{v_i}{v_{in}} = \frac{\rho_i r_i^2}{\rho_{in} r_{in}^2} \tag{3}$$

where

v_{in} , ρ_{in} , r_{in} - are the rate, density and radius of an initial particle, respectively;

v_i , ρ_i , r_i - are velocity density and radius of hydroxide or carbonate particle, respectively.

The obtained dependencies were presented by empiric relationships and included into the AERO code.

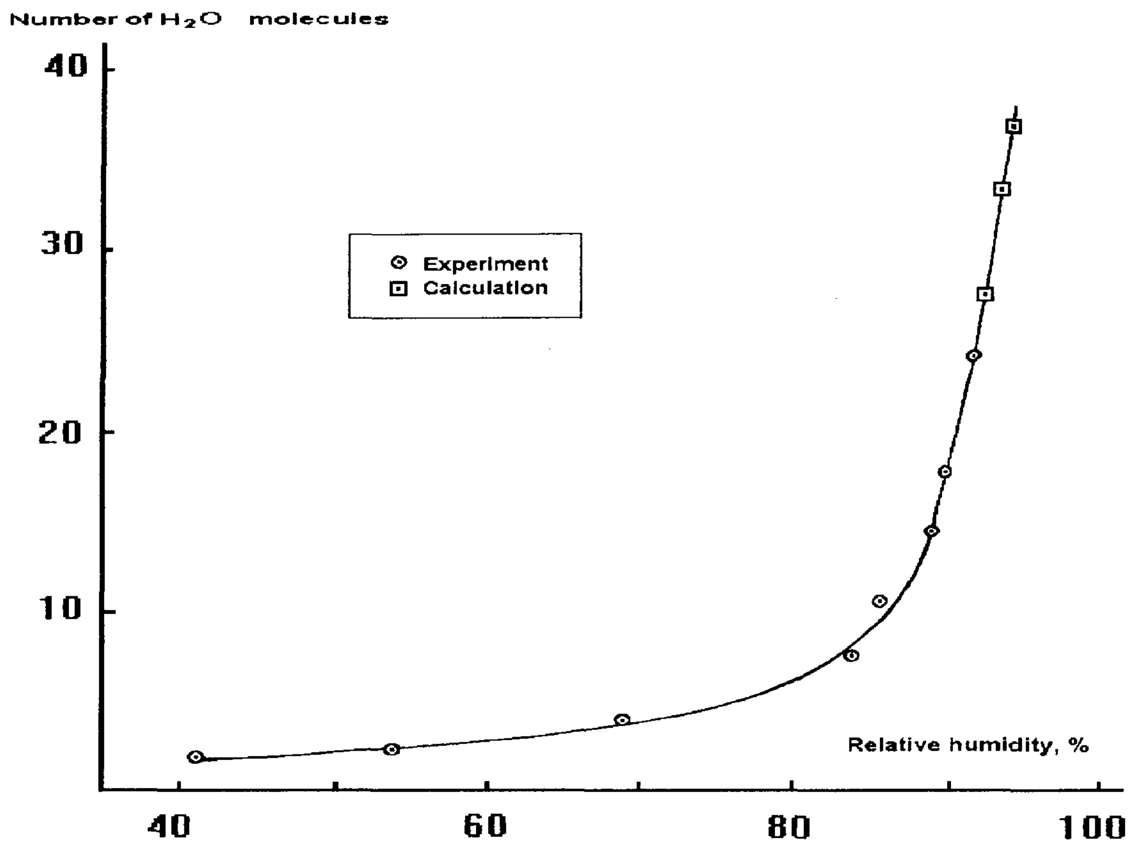

Fig. 2. Number of H_2O molecules in carbonate.

2. CALCULATION ANALYSIS OF POSSIBLE ACCIDENTS

With the use of the BOX and AERO codes an analysis of probable accidental situations for the operating BN-350 and BN-600 NPPs and for the currently designed NPP with the BN-800 reactor was carried out. Here main stages and results of the analysis for the BN-800 are briefly outlined. The presented probability values have been obtained using the probabilistic reliability analysis methods (PRA).

2.1. Initial events of accidents

In this statement of the problem the main point is correct specification of the design defect size. We proceed from that for fast reactor sodium systems a concept of "leak-before-break" can be used. Consideration of this problem is given in paper [5] presented at this Meeting. At determining an initial event of the design basis accident it is assumed that the defect has a form of a circle with a diameter equal to double thickness of the pipe wall. The probability of such defect formation is 10^{-2} 1/reactor-year.

For a beyond design basis accident the calculated defect corresponds to the guillotine-type pipe rupture. We proceed from that the pipe rupture is a consequence of the development of some initial defect not detected by existing monitoring systems, i.e., a result of several failures that corresponds to the beyond design basis concept. The probability of this event is 10^{-5} 1/reactor-year.

2.2. Paths of accidents development

2.2.2. Design basis accident

Systems for suppression and localization of sodium leak and fire consequences adopted in the BN-800 project have been outlined in a number of papers, for example, in [6, 7]. It may be briefly said that they include both passive (powders, drainage systems) and active systems (switching - off of intake and operating exhaust ventilation, switching - on of emergency exhaust ventilation with aerosol filters). According to regulatory documents currently effective in our country [8] the design bases accident is characterized by one failure. At least one of the sodium leak and fire detection systems comes into operation, i.e., a fire signal is formed.

2.2.3. Beyond design basis accident

It is characterized by a number of failures [8]. It is assumed that detection systems do not come into operation, and hence the active systems do not operate. It is assumed that the passive systems do not also come into operation. The probability of accident development in this way is 10^{-9} 1/reactor-year.

2.3. Accident consequences

2.3.1. Design basis accident

Amount of burnt sodium is no more than 600 kg. Release into the atmosphere is not over 0.06 kg. For the BN-800 with the ^{24}Na radionuclide primary sodium specific activity of 30 Ci/l it corresponds to a release of about 1.8 Ci. It is less than the permissible release by the regulatory document [9] even for normal operation (5 Ci/day).

2.3.2. Beyond design basis accident

A volume of leaked sodium is ≤ 33 m³. Total release is ≤2700 kg (for sodium). The values of in - sodium radionuclides specific activity and their release into the atmosphere are presented in Table 1.

TABLE 1. SPECIFIC ACTIVITY OF RADIONUCLIDES AND THEIR RELEASE INTO THE ATMOSPHERE AT THE BEYOND DESIGN BASIS ACCIDENT

Nuclide	^{24}Na	^{22}Na	^{131}I	^{134}Cs	^{137}Cs
Specific activity, Ci/l	30	2×10^{-3}	4×10^{-4}	1.1×10^{-3}	5×10^{-3}
Release, Ci	8.1×10^{4}	5.4	1.1	9.4	43.2

Doses to population on the site for the total body as a function of distance are presented in Table 2.

TABLE 2. DOSES TO POPULATION ON THE SITE AS A FUNCTION OF DISTANCE DURING THE FIRST POST-ACCIDENT YEAR

Distance, km	3	5	13	20	25
Dose, rem	2.17	1.44	0.5	0.23	0.14

In compliance with the regulatory document [10] at a large radiation accident it is unconditionally required to carry out protective measures (limitation of consumption of contaminated foodstuffs and drinking water) if the total-body dose during the first post-accident year is over 5 rem. The data of the table indicate that in our case it is not required. If the irradiation level does not exceed 0.5 rem there is no necessity to carry out any protective measures . If the irradiation level is within the above boundaries then the decision on carrying out the protective measures is made taking into account a specific situation and local conditions. Thus, in our case some danger exists only for population of the area within a radius of 13 km. Let us remind that the probability of such an accident is negligible.

3. AN ANALYSIS OF OCCURRING SODIUM LEAKS

Much attention is being given to the analysis of sodium leaks that occurred at sodium systems. It is mainly carried out with the aim of evaluating the decision made at designing on leak detection and fire control systems, to define the causes of leaks, to estimate personnel actions. An important aspect of this analysis is evaluation of applicability to sodium systems of the " leak- before-break" criterion. As it was mtntioned above this problem is considered in the paper [5] presented at this Meeting.

A volume of most leaks did not exceed 10 l. Small volumes of leakages might be explained by that almost all leaks were detected at early stages of their initiation. This indicates good operation of the leak detection systems. Sodium burning was noted only in one half of the total number of leaks that is also the result of small scales of leaks.

There were no cases of guillotine type pipe ruptures. No leak caused any failure of building or technological structures. There were also no " secondary" leaks, i.e., the leaks that would be caused by any effect of leaking sodium upon building or technological structures.

Personnel errors are a very important factor, in some cases resulting in leak occurrence and often affecting its development. Large leaks, as a rule, appeared during commissioning and maintenance activities, i. e., at direct participation of operating or maintenance personnel.

The most important conclusion following from sodium leak experience is that none of the leaks and none of occurring sodium fires endangered nuclear safety of a reactor and lead to any serious deterioration of radiation situation.

4. EXPERIMENTAL STUDIES.

4.1. Sodium spray fires.

Theoretical analysis and operation experience indicate that large leakages of dispersed sodium at reactor systems are unreal. Nevertheless, sodium spray fire investigation is under way [11]. For the tests there are used leak-tight chambers in form of vertical cylinders with elliptic covers and bottoms. The principal aim of experiments is the determination of a fraction of sodium burning in form of drops. The sodium jet is directed vertically upwards. An injection device is located near the chamber bottom. Across the jet a screen is placed by impact against which the jet disintegrates into drops. The distance from the injector to the screen can be varied.

Initially the tests were carried out in a chamber of 2 m^3 in volume and ~ 1m in diameter. The injecting device came into action at a rupture of the membrane which bursted at a pressure of 0.45 to 0.65 MPa (depending on its specific design). Temperature of supplied sodium was within 400 up to 500° C, an amount of injected sodium was 400 to 2000 g, injection time - from 0.07 to 0.7 seconds.

A maximum value of gas pressure in the chamber in the course of experiments was within the limits from 0,16 MPa (at injection of 400 g of sodium) up to 0.41 MPa (injection of 2000 g of sodium). The maximum local gas temperature (in the area of jet impact against the screen) was equal to 1250°C.

The obtained experimental data did not allow to obtain a final answer to the question about a fraction of sodium burning in form of drops, because large amount of sodium after jet disintegration got upon the walls of the chamber. That is why the tests were continued in a chamber of 8 m^3 in volume and ~ 2m in diameter. Sodium was fed not by means of a membrane rupture but by opening the valve. Mass of sodium supplied was up to 12 kg, a temperature of 500°C. A maximum pressure was obtained equal to 0.16

MPa, a maximum temperature in the upper part of the chamber was ~ 700°C. Results obtained by the present time indicate that no more than 10% of injected sodium is burnt in form of drops. However, the tests are continued.

4.2. Sodium leaks under thermal insulation.

The effect of thermal insulation upon the mechanism of sodium leaking from a hole in the pipe is great of interest. It is especially concerned with sodium dispersion at leaking out. This phenomenon is studied experimentally now. For this purpose at IPPE in the current year a series of experiments have been started [12]. A facility at which the tests are carried out consists of a test section (a tube of 145 x 5 mm with a hole of ∅ 3 mm on the upper surface and heat insulation of glass fibre), a tank with sodium and of a gas receiver.

In the first series of the tests, heat insulation was placed in one layer 50 mm thick. In contract to the design adopted at the reactor plants there was no jacket on the heat insulation surface. Sodium was supplied into the test section by argon pressure.

Visual observations were carried out, temperatures in different zones of the test section and of air in the cell, sodium flow rate and time of leakage were measured. Initial data and maximum experimental values of the temperature under thermal insulation of three tests carried out by now are presented in Table 3.

TABLE 3. DATA OF TESTS ON INVESTIGATION OF THE THERMAL INSULATION EFFECT.

$T_{leak\ Na}$, °C	$P_{leak\ Na}$, MPa	$t_{leak\ Na}$, min	$G_{leak\ Na}$, kg/s	$V_{leak\ Na}$, l	$T_{max\ under\ insulation}$, °C
520	0.4	7,5	0,08	40	800
515	0.55	8,0	0,09	50	850
400	0.55	10	0.1	70	600

In these experiments no heat insulation rupture , sodium jet leakage or dispersion took place. Sodium was leaking out through places of untightness in thermal insulation which interacted with the leaking sodium rather vigorously. It was especially manifested in that part of the section which was located below the defect.

It is known that wide experimental work on studying the influence of thermal insulation on sodium leakage was carried out at RIAR (Research Institute of Atomic Reactors, Dimitrovgrad) in late 70- ties [12]. It rather differs from our work by initial parameters values (defect dimension, leakage pressure) as well as by thermal insulation material. That is why the results of experiments concerning insulation rupture, leakage mode also differ. We are going to continue these experiments.

4.3. Concrete types not interacting with sodium.

Concrete structures of sodium-containing rooms have steel lining (primary circuit rooms are lined completely, and in the secondary circuit rooms floor and walls are lined to a height by 0.5 m exceeding the level of the sodium surface at a maximum possible design leakage). However, some situations are possible when lining has defects formed prior to or in the process of sodium leakage. That is why investigations aimed at development of burning sodium - resistant concretes were carried out [13].

Experiments were carried out with concretes of various composition. As a result it has been found out that the best characteristics has alumina-cement-based concrete with vermiculite filler. Experimental blocks of this concrete were subjected to burning sodium action during two hours. Any explosive effects were absent. After cleaning of the concrete block from sodium on its surface that was in contact with sodium a number of cavities in form of craters 3-4 mm deep and in diameter were detected. Chemical analysis has shown that the depth of sodium penetration into concrete reaches ~ 15 mm. One of these blocks was subjected to the repeated action of sodium under the same conditions. The result was qualitatively the same. No cracking of concrete blocks of this composition occurred in the course of experiments.

4.4. Aerosol filters

It is necessary to ensure the aerosol release filtration in a possible sodium fire at fast reactor NPP. For this purpose the work on design and investigation of appropriate aerosol trapping systems were carried out. A two-stage filtration system was adopted. The water scrubbers were used as a first stage devices. At the second stage the dry filters are usually used.

A series of experiments have been carried out in order to investigate the parameters of such system [3], It was shown that the system has high efficiency (99.999%).

5. COMPARATIVE ANALYSIS OF COMMON-CAUSE AND SODIUM FIRE HAZARDS.

An ability of sodium at operating temperatures to conflagration at a contact with air is considered by some specialists as the most serious disadvantage of this type reactors. On this basis sometimes a conclusion is even drawn about an impossibility of extensive development of sodium-cooled fast reactor NPPs.

However, neither operation experience, nor theoretical and experimental studies speak in favour of this pessimistic conclusion. Occurring in practice sodium leaks and fires did not create any danger for nuclear or radiation safety of the plants. On the other hand, at thermal reactors operation a number of large fires occurred (for example, in USA at the "Browns-Ferry" NPP in 1975, in the former USSR at the Beloyarsk NPP in 1978, at the Armenian NPP in 1982) which caused great material damage, and at an unfavourable development of events could endanger reactor safety [14]. At the same time the analysis performed suggests that the probability of very large sodium leakages (of the order of hundreds tons) which only could present such a danger is very small.

These considerations were used as the basis of studies carried out at IPPE on the comparative analysis of common-cause and sodium fires at the fast reactor NPP. Properties of sodium and of other materials used in NPP as of combustible materials were analyzed in comparison. Dangers of different kinds of fires were considered taking into account the conditions of specific reactor designs, including relative arrangement within the reactor building of the systems determining safety of the reactor and of combustible materials (including sodium), fire resistance barriers, fire detection and fire control systems, ventilation schemes and operating conditions. The studies were based upon the probabilistic analysis methods.

As a result it was established as follows:

- sodium fire hazard by released toxic materials under similar conditions does not exceed fire hazard of other materials used at NPP;
- thermal effects of a sodium fire are considerably lower than of a common-cause fire and they are approaching one another only at a sodium spray fire;
- a danger of a reactor building destruction because of a sodium fire is within the limits of residual risk (the probability $< 10^{-9}$ 1/reactor per year);
- for really feasible emergency situations a sodium fire does not make any cardinal contribution into the total fire danger of NPP;
- sodium fire dangers for personnel do not exceed those from a common-cause fire;
- a sodium fire does not create any danger for reactor nuclear safety.

6. CONCLUSION

The results of the above studies have confirmed in our opinion, a possibility of extensive safe development of sodium-cooled fast reactors.

We believe that further work should be carried on mainly in the area of computer codes improvement, of confirmation of the "leak-before-break" concept applicability, of the analysis of occurring sodium real leaks and fires, of experiments on sodium real leak and fire conditions simulation.

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